AFRL-AFOSR-VA-TR-2015-0279

Real-Time Optimization in Complex Stochastic Environment

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06/24/2015
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTA2
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
13-06-2015

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*
April 2012 – March 2015

4. TITLE AND SUBTITLE
REAL-TIME OPTIMIZATION IN COMPLEX STOCHASTIC ENVIRONMENTS

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0113

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Christos G. Cassandras

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Boston University, Boston, MA 02215

8. PERFORMING ORGANIZATION REPORT NUMBER
N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Optimization and Discrete Mathematics
AFOSR
875 Randolph Street Suite 325, Room 4052
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DISTRIBUTION A

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The research reported here aims at enabling a systematic on-line use of optimization techniques for real-time applications in complex stochastic environments that recognizes requirements for new generations of systems critical to the national infrastructure and consistent with the emerging information-based, network-centric view of warfare. The main outcomes of the project are: (a) Asynchronous, event-driven distributed optimization algorithms with the ability to escape frequently occurring local equilibria. (b) Novel on-line trajectory optimization schemes for cooperative multi-agent systems which are scalable and robust with respect to the uncertainty model used. (c) A general-purpose event-driven receding-horizon optimization framework. (d) A general unified Infinitesimal Perturbation Analysis framework for efficient gradient-based optimization of complex stochastic systems.

15. SUBJECT TERMS
Distributed Optimization Algorithms, Asynchronous Optimization Algorithms, Event-driven Optimization, Simulation-based Optimization, Multi-Agent Systems, Perturbation Analysis, Stochastic Hybrid Systems

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	UU	14	Christos G. Cassandras

19b. TELEPHONE NUMBER *(Include area code)*
617-353-7154

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FINAL REPORT

AFOSR GRANT: FA9550-12-1-0113

TITLE: **REAL-TIME OPTIMIZATION IN COMPLEX STOCHASTIC ENVIRONMENTS**

REPORTING PERIOD: April 2012 – March 2015

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June 2015

1. OBJECTIVES

The research pursued under grant FA9550-12-1-0113 aims at enabling a systematic *on-line* use of optimization techniques for real-time applications in complex stochastic environments. This is in contrast to *off-line* optimization for problems involving stochastic settings with complex system dynamics and constraints where one can usually afford computationally intensive methods, including time-consuming simulation. In an on-line setting, however, fast solutions are needed for time-critical decision making, a requirement complicated by the need to frequently re-solve what are already hard problems, since conditions in the operating environment are ever-changing. Thus, new approaches are called for which include: trading off optimality and computational speed; making creative use of powerful simulation-based models and solution algorithms; and exploring new paradigms for appropriate optimality criteria. The work in this project has led to the development of such approaches, while at the same time recognizing requirements for new generations of systems critical to the national infrastructure and consistent with the emerging information-based, network-centric view of warfare.

Three major research objectives were pursued:

1. **Asynchronous, event-driven distributed optimization.** Distributed optimization is one of the means to break down a complex problem into a number of interrelated simpler ones, thus addressing scalability and the limited resources of networked wireless devices. This, however, comes at the expense of increased communication and the need for synchronization across the components over which the optimization problem is distributed. Developing asynchronous (specifically, *event-driven*) approaches alleviates much of this problem by controlling the exchange of information among nodes in a networked environment to occur only when absolutely necessary, dictated by “events” defined through certain well-defined conditions. The main challenges in this research direction are to specify the proper events that trigger communication and updates in the optimization process, as well as to guarantee global optimality of the resulting optimization algorithms.

2. **Temporal decomposition and receding-horizon optimization.** Whereas distributed optimization decomposes complex problems over the components of a system, another form of decomposition is over time. Our approach is to reduce the solution of a complex stochastic problem into a number of smaller deterministic problems solved only when new data are obtained or new random events are observed (along the lines of the event-driven idea already mentioned). Thus, in using *receding horizon* optimization, unlike conventional receding horizon methods which require continuous time-driven iterations, we iterate only when certain events occur; this can drastically reduce computation without affecting the optimality properties of the methods employed.

3. **Abstraction and on-line gradient-based optimization.** Yet another way to combat complexity is through abstraction schemes that preserve sufficient modeling accuracy to deliver near-optimal solutions to optimization problems. In this effort, we make use of Perturbation Analysis (PA) techniques to obtain gradient estimates from already available data without requiring stochastic models that are difficult to build. Recent research has led to a PA framework for very general stochastic hybrid systems with robustness properties that open up the possibility for solving optimization problems thus far considered of prohibitive complexity for PA techniques. As detailed in this report, we have indeed been able to solve such problems, including some that involve multi-player optimization, allowing us to study problems in a stochastic game setting.

2. ACCOMPLISHMENTS AND NEW FINDINGS

2.1. Escaping Local Optima in Distributed Optimization.

Asynchronous distributed optimization schemes can ensure scalability and reduce the need for excessive communication. In our prior work (e.g., see [29]) we developed such a scheme which is event-driven in that it limits communication to instants when some state estimation error function at a node exceeds a threshold. We also developed an interactive simulation environment, available at http://www.bu.edu/codes/research/distributed-control/ through which we have performed experiments and tests related to this distributed optimization framework. Moreover, we continue to use a laboratory test bed (created with partial support from prior AFOSR grants) with small wireless mobile robots (Khepera III) acting as "agents" in a "real-world" cooperative setting (see http://www.bu.edu/codes/platforms/.) Performing experiments in either the simulation or laboratory test bed environment, it has been easy to observe that many of the interesting problems we wish to address are non-convex and exhibit multiple local optima. The large class of coverage control problems arising in multi-agent cooperative systems is a case in point.

In order to address this major problem, we have developed a systematic approach for escaping a local optimum, rather than randomly perturbing controllable variables away from it. We were able to show [36] that the objective function for many problems can be decomposed to facilitate the evaluation of the local partial derivative of each node in the system and to provide insights into its structure. This structure is exploited by defining "boosting functions" applied to the aforementioned local partial derivative at an equilibrium point where its value is zero so as to transform it in a way that induces nodes to explore poorly covered areas of the mission space until a new equilibrium point is reached. This boosting process ensures that, at its conclusion, the objective function is no worse than its pre-boosting value (even though the global optima can still not be guaranteed). We have established and analyzed three families of boosting functions with different properties. We have also conducted extensive simulation-based experiments to demonstrate how this approach improves the solutions obtained through distributed optimization problems.

2.2. Trajectory Optimization in Cooperative Multi-Agent Systems.

The distributed optimization framework discussed in Section 2.1 addresses *static* or *parametric*, rather than *dynamic*, optimization problems. For instance, in an optimal coverage problem, the goal is to determine optimal positions of agents (nodes) in a given mission space; the objective function is expressed in terms of all feasible positions which are, therefore, viewed as parameters to be optimized. In contrast, agents may be in continuous motion aiming to optimize an objective function describing their time-varying interaction with their environment.

In the course of the project, we have tackled such problems aiming to investigate whether the success of event-driven distributed algorithms could be carried over to such ambitious dynamic optimization problems. A direct extension of the class of optimal coverage problems is that of "persistent monitoring" problems, where the objective is to control the movement of multiple cooperating agents to minimize an uncertainty metric in a given mission space. We started with a one-dimensional mission space, where we formally showed that the optimal solution is for each agent to move at maximal speed from one switching point to the next, possibly waiting some time at each point before reversing its

direction [12]. Thus, the solution is reduced to a simpler parametric optimization problem: determining a sequence of switching locations and associated waiting times at these switching points for each agent. This amounts to a hybrid system which we analyzed using Infinitesimal Perturbation Analysis (IPA) to obtain a complete on-line solution through a gradient-based algorithm. Interestingly, our effort to extend event-driven optimization techniques led us to a natural use of IPA, another key thrust of the project (see Section 2.4). We were also able to show that the solution obtained is robust with respect to the uncertainty model used.

Motivated by the success of deriving computationally efficient solutions in the one-dimensional persistent monitoring problem, we subsequently pursued the case of two-dimensional mission spaces where the objective is to control the trajectories of multiple cooperating agents to minimize an uncertainty metric. Unfortunately, the simple solutions of the one-dimensional case do not carry over to a two-dimensional mission space. An alternative is to optimally assign each agent a linear trajectory, motivated by the one-dimensional analysis. However, we proved that elliptical trajectories outperform linear ones [41]. With this motivation, we formulated a parametric optimization problem in which we seek to determine such optimal elliptical trajectories and then showed that the problem can again be solved using IPA to obtain performance gradients on line and ultimately derive a complete and scalable solution. Since the solutions obtained are generally locally optimal (as discussed in Section 2.1), we have incorporated a stochastic comparison algorithm for deriving globally optimal elliptical trajectories. Our approach allows for uncertainties modeled as stochastic processes, and leads to a *scalable* on-line methodology orders of magnitude more efficient than any off-line computationally intensive solutions.

Over the past year of the project, we generalized the results above by approaching the trajectory optimization problem through a representation of an agent trajectory in terms of general function families characterized by parameters that we can optimize. We have shown [35] that the problem of determining optimal parameters for these trajectories can be solved, once again, using Infinitesimal Perturbation Analysis (IPA) to determine gradients of the objective function with respect to these parameters evaluated on line so as to adjust them through a standard gradient-based algorithm. We have applied this approach to the family of Lissajous functions as well as a Fourier series representation of an agent trajectory and demonstrated that this *scalable* approach provides solutions that are near-optimal relative to those obtained through a computationally intensive two point boundary value problem solver. The same idea has also been successfully applied to a class of optimal exploration, pick-up and delivery problems [50].

2.3. Event-driven Cooperative Receding-Horizon Optimization.

This part of the project has focused on making optimal decisions in a real-time stochastic setting in the absence of any information about the future at the time a decision needs to be made. To model the unknown future, we normally either build an analytical probabilistic model encompassing uncertainties or we resort to simulation. Building an analytical model is difficult because we must often make questionable assumptions, lack the necessary information, or resort to unreliable data to construct appropriate distributions. Simulation, on the other hand, is a time-consuming task. Both are “estimate-and-plan” approaches in which a policy is derived to dictate optimal decisions to make in real time as a function of an observed system state. An alternative is a “hedge-and-react” approach whereby we simply wait for a random event to occur and then react, provided that the decision making process upon reaction is sufficiently fast relative to the random event frequency. In this approach, the process is viewed as deterministic in between randomly occurring events, amounting to a decomposition of a complex problem

over time. Thus, at certain points in time, we solve an optimization problem over a given time horizon, and then continuously extend this time horizon forward. This gives rise to Receding Horizon (RH) optimization algorithms which we have developed in our prior work.

There are several limitations of the RH optimization approaches previously developed. Our work in this project has led to overcoming many of these limitations and establishing a novel general-purpose event-driven RH optimization framework [34]. The limitations we have overcome include potential instabilities in agent trajectories and poor performance due to inaccurate estimation of a reward-to-go function. In this framework, a controller sequentially solves optimization problems over a planning horizon and executes the control for a shorter action horizon, where both are defined by certain events associated with new information becoming available. In contrast to earlier similar controllers developed, we were able to reduce the originally infinite-dimensional feasible control set to a *finite* set at each control update event. We proved several properties of this new controller and generated extensive simulation results showing its improved performance.

Another class of real-time dynamic optimization problems arises in systems whose components (e.g., mobile agents) critically depend on battery-supplied energy. We studied the problem of optimally controlling how to discharge and recharge a non-ideal battery so as to maximize the work it can perform over a given time period and still maintain a desired final energy level. Although we originally expected to resort to RH optimization approaches as described above, we were able to show that a much simpler solution can be obtained which is of bang–bang type [4] with the property that the battery is always in recharging mode during the last part of the finite horizon over which the problem is solved. We then extended the problem to settings where recharging is only occasionally feasible and showed that it can be reduced to a nonlinear optimization problem which can be solved at least numerically. We were also able to extend our study to the problem of optimally controlling a set of non-ideal rechargeable batteries that can be shared to perform a given amount of work over some specified time period. We sought to maximize the minimum residual energy among all batteries at the end of this period by optimally controlling the discharging and recharging process at each battery. We showed that the optimal solution must result in equal residual energies for all batteries as long as such a policy is feasible. This greatly simplifies the task of subsequently deriving explicit solutions for the problem. Finally, we incorporated this work into the problem of optimal routing and energy allocation for maximizing the lifetime of wireless sensor networks with non-ideal batteries [26].

2.4. Abstraction and on-line gradient-based optimization

Under past AFOSR grants, we were able to establish a general framework for an Infinitesimal Perturbation Analysis (IPA) theory for stochastic hybrid systems to control and optimize their performance in a real-time setting that allows for uncertainties and changes in their operating environment (see [14]). During this work, we came to the realization that previously intractable stochastic games can also be solved as multi-agent optimization problems so that system-centric solutions can be compared to user-centric ones and quantify the associated gap between the two, known as the “price of anarchy.” We solved several stochastic resource contention problems, including the long-standing lot-sizing problem as a stochastic game for which we have formally proved that in this case the “price of anarchy” is zero [2].

With this motivation, we sought to extend the definition of a Stochastic Hybrid Automaton (SHA) to overcome some limitations that make it difficult to use for on-line

control and optimization. In particular, guard sets (describing conditions for transitioning from one discrete state to another) do not specify the exact event causing a transition. To overcome this, we have introduced a clock structure (borrowed from timed automata), timer states, and guard functions that disambiguate how transitions occur. In the modified SHA, we have formally shown that every transition is associated with an explicit element of an underlying event set. This also makes it possible to uniformly treat all events observed on a sample path of a stochastic hybrid system and generalize the performance sensitivity estimators derived through IPA. Thus, we managed to eliminate the need for a case-by-case treatment of different event types and have provided a unified set of matrix IPA equations [5]. We have demonstrated the use of this unified framework in a number of application areas, including the problem of optimal "timeout control" [10] which often arises in time-critical settings, as well as in transportation applications such as the traffic light control problem [19],[44].

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• **Accepted, but not yet published:**

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[48] Pourazarm, S., and Cassandras, C.G., "Energy-based Lifetime Maximization and Security of Wireless Sensor Networks with General Non-ideal Battery Models", subm. to *IEEE Trans. on Control of Network Systems*, 2015.

[49] Sun, X., and Cassandras, C.G., "Optimal Dynamic Formation Control of Multi-Agent Systems in Environments with Obstacles", subm. to *54th IEEE Conference on Decision and Control*, 2015.

[50] Nenchev, V., and Cassandras, C.G., "Optimal exploration and control for a robotic pick-up and delivery problem in two dimensions", subm. to *54th IEEE Conference on Decision and Control*, 2015.

[51] Khazaeni, Y., and Cassandras, C.G., "An Optimal Control Approach for the Data Harvesting Problem", subm. to *54th IEEE Conference on Decision and Control*, 2015.

[52] Pourazarm, S., and Cassandras, C.G., "Lifetime Maximization of Wireless Sensor Networks with a Mobile Source Node", subm. to *54th IEEE Conference on Decision and Control*, 2015.

[53] Fleck, J.L., and Cassandras, C.G., "Infinitesimal Perturbation Analysis for Personalized Cancer Therapy Design", subm. to *5th Conference on Analysis and Design of Hybrid Systems*, 2015.

[54] Pourazarm, S., and Cassandras, C.G., "System-Centric Minimum-Time Paths for Battery-Powered Vehicles in Networks with Charging Nodes", subm. to *5th Conference on Analysis and Design of Hybrid Systems*, 2015.

4. PERSONNEL SUPPORTED

• Principal Investigator:

Christos G. Cassandras, Professor, Boston University

• Graduate Students:

- Ali Kebarighotbi (PhD obtained, 2012 – supported by predecessor AFOSR grant)
- Tao Wang (PhD obtained, 2013)
- Yanfeng Geng (PhD obtained, 2013)
- Julia Lima Fleck
- Yasaman Khazaeni
- Sepideh Pourazarm
- Xinmiao Sun
- Yue Zhang

The PhD dissertation completed by Ali Kebarighotbi is entitled "Perturbation Analysis in Fluid Scheduling and Optimization of Stochastic Hybrid Systems". It studies on-line optimization problems for stochastic hybrid systems, i.e., systems that involve both continuous and discrete dynamics and are suitable for modeling almost any physical system of interest. For the class of Stochastic Flow Models (SFM), a classic problem for optimally allocating a resource to multiple competing user queues is considered and placed in the framework of SFMs. Infinitesimal Perturbation Analysis (IPA) is used to calculate the gradient estimates for the average holding cost of this system with respect to resource allocation parameters. The monotonicity property of these estimates was exploited to prove the optimality of a well-known rule called the $c\mu$-rule" under non-idling policies. Furthermore, nonlinear cost functions are considered, yielding simple distribution-free cost sensitivity estimates. In addition, a Transmission Control Protocol (TCP) communication link is used to examine the effectiveness of IPA in calculating derivative estimates of a "goodput" objective with respect to a timeout parameter. The analysis is also extended to the case of multi-node communications. This analysis reveals the potential in using IPA to control delay thresholds in a broader range of time-critical applications. Finally, the dissertation proposes a general framework for analysis and on-line optimization of Stochastic Hybrid Systems which facilitates the use of IPA. This framework enables one to uniformly treat all events observed on the sample path of the SHS. As a result, a unifying matrix notation for IPA equations is developed which eliminates the need for the case-by-case analysis of event classes as usually done in prior work.

The PhD dissertation completed by Tao Wang is entitled "Control and Optimization Approaches for Power Management in Energy-Aware Battery-Powered Systems". This dissertation is devoted to on-line optimal power management of energy-aware battery-powered systems (BPSs). Its first part focuses on the power management of BPSs based on an analytical non-ideal battery model, the Kinetic Battery Model (KBM), and gives solutions to the cases with both fully and partially available rechargeability. In multi-battery systems, a similar methodology is employed to show an optimal policy which

enforces equal terminal energy values of all batteries as long as such a policy is feasible. Furthermore, the KBM is introduced into a routing problem for lifetime maximization in wireless sensor networks (WSNs). The solution not only preserves the properties of the problem based on an ideal battery model but also shows the applicability of the KBM to large network problems. The second part of the dissertation is focused on the energy aware behavior of mobile devices and vehicles (e.g., electric vehicles (EVs)). It two motion control problems of (a) cruising range maximization and (b) traveling time minimization. Approximate controller structures are proposed such that the original optimal control problems are transformed into nonlinear parametric optimization problems, which are much easier to solve. Finally, the vehicle routing problem with energy constraints is investigated. Optimal routes and recharging times at charging stations are sought to minimize the total elapsed time for vehicles to reach a destination. For a single vehicle, a mixed-integer nonlinear programming (MINLP) problem is formulated. A decomposition method is proposed to transform the MINLP problem into two simpler problems respectively for the two types of decision variables. Based on this, a multi-vehicle routing problem is studied using a flow model, where traffic congestion effects are included.

The PhD dissertation completed by Yanfeng Geng is entitled “Optimization Methods for Intelligent Transportation Systems In Urban Settings”. The dissertation develops a novel “Smart Parking” system in the context of dynamic stochastic resource allocation problems. As opposed to simply providing parking information to drivers, the proposed approach is to assign and reserve an optimal parking space based on a user’s cost function that combines proximity to destination and parking cost. This is accomplished by solving a Mixed Integer Linear Programming (MILP) problem at each decision point defined over a sequence of time instants. The solution of each MILP problem is an optimal allocation based on current state information, and is updated at the next decision point with a guarantee that there is no resource reservation conflict and that no user is ever assigned a resource with a higher than this user’s current cost function value. An indoor laboratory testbed was built to demonstrate the functionality of a system prototype and a full implementation in a garage was also carried out. The dissertation further addresses the traffic light control problem viewed as a stochastic hybrid system and by developing a Stochastic Flow Model (SFM) for it. Using Infinitesimal Perturbation Analysis (IPA), on-line gradient estimates of a cost metric are derived with respect to the controllable green and red cycle lengths. The estimators are used to iteratively adjust light cycle lengths to improve performance and, in conjunction with a standard gradient-based algorithm, to obtain optimal values which adapt to changing traffic conditions.

5. INTERACTIONS/TRANSITIONS DURING REPORTING PERIOD

Participation/Presentations at Meetings, Conferences, Seminars

C.G. Cassandras gave invited talks/ plenary addresses/lectures at the following meetings/organizations:

- University of Athens, April 2012, Athens, Greece (Invited Seminar).
- University of Cyprus, April 2012, Nicosia, Cyprus (Two Invited Seminars).
- Boston University CISE Anniversary Symposium, May 2012, Boston, MA (Invited Talk).
- Tsinghua University, May 2012, Beijing, China (Invited Seminar).
- Beijing Jiaotong University, May 2012, Beijing, China (Invited Seminar).
- 24th Chinese Control and Decision Conference, Taiyuan, China, May 2012 (**Keynote Address**)

- Chinese Academy of Sciences, Beijing, China, May 2012 (Invited Seminar).
- National Taiwan University, Taipei, Taiwan, May 2012 (Invited Seminar).
- National Chiao Tung University, Hsinchu, Taiwan, June 2012 (Invited Seminar).
- 2013 American Control Conference, Montreal, Canada, June 2012 (Invited Panel Presentation).
- Kyoto University, Kyoto, Japan, August 2012 (Invited Seminar).
- Tokyo Institute of Technology, Tokyo, Japan, August 2012 (Invited Seminar).
- 2012 Conference, Society of Instrument and Control Engineers Annual Conference, Akita, Japan, August 2012 (**Plenary Lecture**).
- 2013 Brazil Automation Conference, Campina Grande, Brazil, August 2012 (**Plenary Lecture**).
- Oak Ridge National Laboratory, Oak Ridge, TN, September 2012 (Invited Talk).
- NSF Workshop on "Ideas and Technology of Control Systems", Maui, HI, December 2012 (Invited Talk).
- 51st IEEE Conf. Decision and Control, Maui, HI, December 2012 (Invited Panel Talk on “Ethics in Publishing”).
- Zhejiang University, Huangzhou, China, January 2013 (**Two Distinguished Lectures**).
- Fudan University, Shanghai, China, January 2013 (Invited Seminar).
- Workshop on Control of Cyber-Physical Systems, Baltimore, MD, March 2013 (Two Invited Talks).
- University of Cyprus, April 2012, Nicosia, Cyprus, April 2013 (Invited Seminar).
- Tokyo Institute of Technology, Tokyo, May 2013 (Invited Seminar).
- MathWorks Research Faculty Summit, Newton, MA, June 2013 (Invited Talk).
- UC Berkeley, Berkeley, CA, October 2013 (Invited Seminar).
- University of Connecticut, Storrs, CT, November 2013 (Invited Seminar).
- GeorgiaTech, Atlanat, GA, November 2013 (Invited Seminar).
- 52nd IEEE Conf. on Decision and Control, Florence, Italy, December 2013 (Invited Panel Talk).
- Boston University, Boston, MA, March 2014 (**2014 Distinguished Scholar Award Lecture**)
- 33rd Benelux Meeting on Systems and Control, Heijen,The Netherlands, March 2014 (**Plenary Lecture**).
- University of Notre Dame, South Bend, IN, April 2014 (Invited Seminar).
- University of Michigan, Ann Arbor, MI, April 2014 (Invited Seminar).
- MathWorks Research Faculty Summit, Newton, MA, June 2014 (Invited Talk).
- KIOS Center Workshop, University of Cyprus, Nicosia, Cyprus, June 2014 (**Plenary Lecture**).
- University of Cyprus, Nicosia, Cyprus, June 2014 (Invited Seminar).
- UTC Institute for Advanced Systems Engineering Annual Conference, Storrs, CT, October 2014 (**Plenary Lecture**).
- Symposium on the Control of Network Systems, Boston, MA, October 2014 (Invited Talk).
- 53rd IEEE Conf. on Decision and Control, Los Angeles, CA, December 2014 (Invited Talk).
- Federal Highway Administration Workshop on Next Generation Traffic Control Systems, Washington, DC, February 2015 (Invited Panel Presentation).

Transitions

• *Dynamic Resource Allocation optimization algorithm used in developing a “Smart Parking”system with an iPhone application*

C.G. Cassandras and PhD student Yanfeng Geng developed an optimization algorithm

used for a “smart parking” system using an application for the iPhone. The system was deployed in a garage pilot study at Boston University and has undergone several pilot studies.

6. NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES

Provisional patent application: “Method and System for Dynamic Parking Allocation in Urban Settings” Application Number 61/521,424; filed 8/9/2011 (still pending).

7. HONORS/AWARDS

C.G. Cassandras (Lifetime, selected):

- Lilly Fellow (1991), Kern Fellow (2012), Fellow of IEEE (1996), Fellow of IFAC (2008)
- 2011 IEEE Control Systems Technology Award
- IFAC Harold Chestnut Prize (1999)
- Distinguished Member Award, IEEE Control Systems Society (2006)
- Editor-in-Chief of *IEEE Transactions on Automatic Control* (1998-2009)

Honors/Awards received during grant period:

- President, IEEE Control Systems Society, 2012
- 2014 Engineering Distinguished Scholar Award, Boston University
- 2014 IBM/IEEE Smarter Planet Challenge competition, 2nd prize (student team led by Theodora Brisimi)
- Zhu Kezhen Award, 2012
- Keynote/Plenary speaker in four international meetings/conferences

1.

1. Report Type

Final Report

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Primary Contact Phone Number

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617-353-7154

Organization / Institution name

Boston University

Grant/Contract Title

The full title of the funded effort.

REAL-TIME OPTIMIZATION IN COMPLEX STOCHASTIC ENVIRONMENTS

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0113

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

Christos G. Cassandras

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. Fariba Fahroo

Reporting Period Start Date

04/01/2012

Reporting Period End Date

03/31/2015

Abstract

The research reported here aims at enabling a systematic on-line use of optimization techniques for real-time applications in complex stochastic environments that recognizes requirements for new generations of systems critical to the national infrastructure and consistent with the emerging information-based, network-centric view of warfare. The main outcomes of the project are: (a) Asynchronous, event-driven distributed optimization algorithms with the ability to escape frequently occurring local equilibria. (b) Novel on-line trajectory optimization schemes for cooperative multi-agent systems which are scalable and robust with respect to the uncertainty model used. (c) A general-purpose event-driven receding-horizon optimization framework. (d) A general unified Infinitesimal Perturbation Analysis framework for efficient gradient-based optimization of complex stochastic systems.

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- 43 published archival publications included in Final Report
- 2 accepted but not yet published archival publications included in Final Report
-11 submitted but not yet accepted archival publications included in Final Report

Changes in research objectives (if any):

None

Change in AFOSR Program Manager, if any:

Dr. Fariba Fahroo replaced Dr. Donald Hearn in 2013

Extensions granted or milestones slipped, if any:

None

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

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